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US ARMY ELECTRONICS RESEARCH & DEVELOPMENT ACTIVITY

THE EFFECT OF CROSS WIND ON SOUND PROPAGATION

BY

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WHITE SANDS MISSILE RANGE NEW MEXICO

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ENVIRONMENTAL SCIENCES DEPARTMENT
U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT ACTIVITY
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ABSTRACT

Sound from two high-altitude explosions at the White Sands Missile Range, New Mexico, was detected by a surface-based microphone array located about 30 miles to the south of the explosions. The observed azimuth angles of the sounds as they crossed the array were 1° 08' and 1° 35' west of the geographical azimuth between sound source and microphone array. This error was due to easterly winds, and a correction for these winds was determined which reduced the error to 0° 05' and 0° 12'.

CONTENTS

PAGE

ABSTRACT - iii

INTRODUCTION - 1

THEORY - 1

DATA - 3

RESULTS - 5

CONCLUSIONS - 11

REFERENCES - 13

FIGURES

1. Sound Waves in a Stationary Medium - - - - - - - - - - - - - 2
2. Sound Waves in a Moving Medium - - - - - - - - - - - - - - - 4
3. Computed and Observed Azimuths - - - - - - - - - - - - - - - 6

TABLES

I. Meteorological Data, 27 July 1962 - - - - - - - - - - - - - 7

II. Meteorological Data, 23 July 1962 - - - - - - - - - - - - - 8

III. Sound Ray Trajectories for 39.3° Ray, 23 July 1962 - - - - 9

IV. Sound Ray Trajectory for 31.5° Ray, 27 July 1962- - - - - - 10

V. Cross-Wind Corrections- 12

INTRODUCTION

Under certain atmospheric conditions, blast waves from an explosion may be propagated over unusually long distances. This can occur if there is an increase with altitude in the velocity of sound due to an increase with altitude in the temperature or the wind speed or the combination of the two. The observation of sound beyond intermediate surface zones of silence is generally due to the refraction of sound in the upper stratosphere. It has been shown that sound can propagate over long horizontal distances through the natural waveguides that generally exist in the atmosphere [1-4]. The propagation of sound through the atmosphere is considerably influenced by atmospheric winds both in the velocity of the sound wave and the path that it follows. The standard practice in analysis of sound propagation utilizing ray-tracing techniques is to include the component of wind speed in the plane of travel of the sound in computing the speed and the refractive characteristics of the path [4-7]. The wind component normal to the plane of propagation between the source and receiver (cross wind) is usually neglected; however, earlier investigators have described methods which in essence treat the cross wind as a translating mechanism [8-10]. The purpose of this report is to describe the effects of cross wind on the propagation of sound resulting from two high-altitude explosions over the White Sands Missile Range.

THEORY

For atmospheres having only horizontal winds, the local speed of sound is a function of both temperature and wind speed and may be determined from

$$c = c_0 + w \sin i$$

where c_0 = speed of sound due to temperature, and

$w \sin i$ = speed of wind in direction of propagation.

The effect of the wind component normal to the direction of propagation is discussed below.

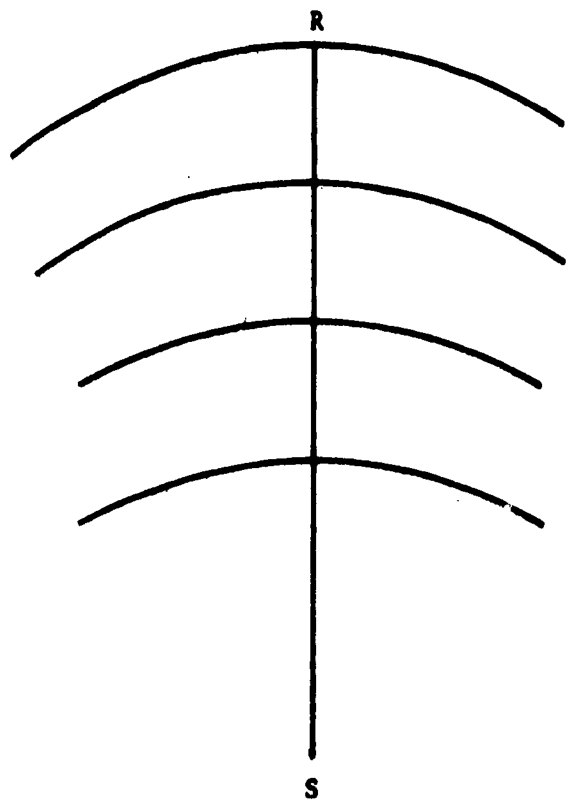
Consider the wave front of sound being emitted in a motionless medium from a point source S as shown in Figure 1. If R is the receiver, the travel time t from S to R along a ray normal to the wave front is:

$$t = \frac{RS}{c} \tag{1}$$

where c is the speed of sound.

FIGURE 1

SOUND WAVES IN A STATIONARY MEDIUM



Now let the medium move at right angles to the line RS (from left to right as shown in Figure 2) at a uniform speed v, with respect to the fixed points R and S. Let y be the distance from S to S', x the distance from R to S and z be the distance from R to S'. Let t_1 be the new time required for the wave front to travel from S to R. During the time t_1, the origin of the wave front will appear to have moved to S' and

$$y = vt_1. \tag{2}$$

Let Δt be the difference in time required for the wave front to travel from S to R with and without the effect of the moving medium, that is:

$$\Delta t = t_1 - t \tag{3}$$

$$x = ct \tag{4}$$

$$y = v\ (t + \Delta t). \tag{5}$$

If we now consider the right triangle RSS' in Figure 2,

$$\tan \theta = \frac{y}{x} = \frac{v(t + \Delta t)}{ct} = \frac{v}{c} + \frac{v\Delta t}{ct} \tag{6}$$

and since $v\Delta t \ll ct$, $\tan \theta = \frac{v}{c}$ (7)

where θ is the approximate error in the azimuth of detected sound due to the motion of the medium and v is the motion of the medium which is the wind acting on the wave front during its travel along the plane of propagation; therefore, the approximate error in azimuth of a detected sound wave is a function of the wind component normal to the sound wave's propagation path through the atmosphere and the speed of sound.

DATA

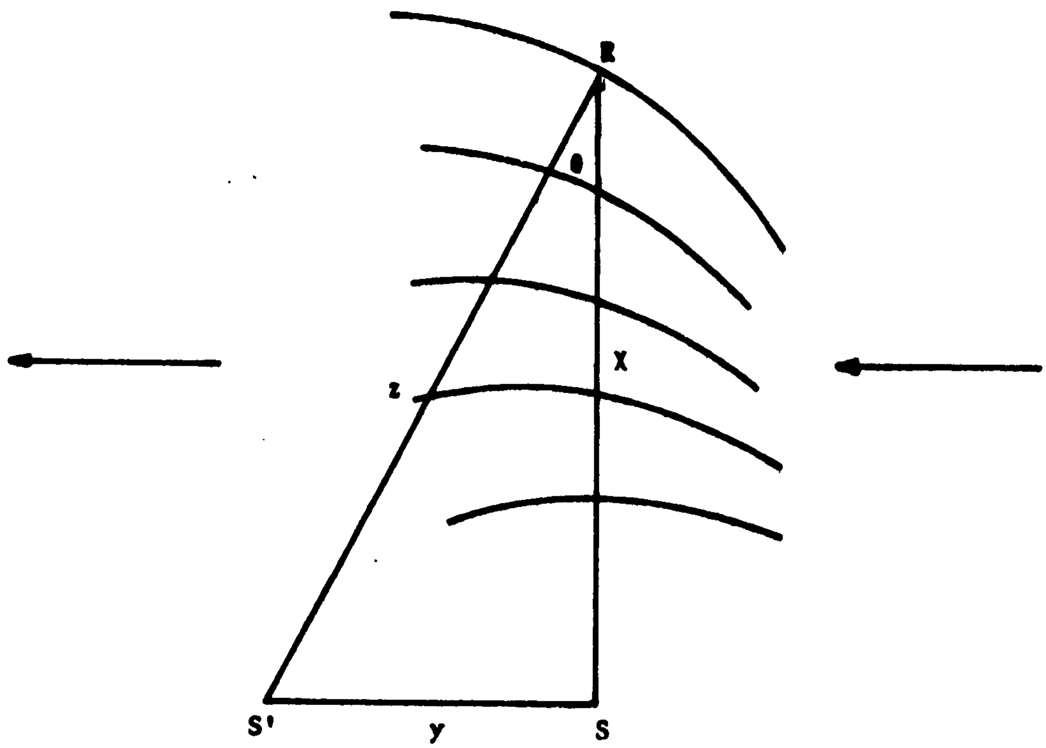
As a part of Project Banshee, a 500-pound high-explosive charge was detonated over the White Sands Missile Range at each of the following times and altitudes:

23 July 1962, 0914 11.57" MST at 104, 499.8 ft MSL

27 July 1962, 0859 57.28" MST at 103, 676.0 ft MSL.

FIGURE 2

SOUND WAVES IN A MOVING MEDIUM



Meteorological data between the surface and 105,000 ft MSL were collected by radiosonde observations during the time periods 0640-0820 and 0900-1030 hours MST on 27 July 1962; examination of these data as listed in Table I indicates rather constant conditions for the period covered. The data used in ray tracing and analysis of cross-wind effect were those collected between 0640 and 0820 hours MST.

Meteorological data on 23 July at 0900 hours were available only up to 55,000 ft MSL, and conditions between 55,000 and 105,000 ft MSL were estimated from data collected at 0630 and 1340 hours. Examination of the data listed in Table II indicates that the estimated data between the surface and 55,000 ft MSL from the 0630 and 1340 observations are comparable to the observed data at 0900. Since atmospheric conditions appear to have changed little between 0630 and 1340 hours, the data above 55,000 ft MSL for 0900 could be estimated reliably from these observations

The sound from the explosions was detected by a microphone array located on the surface about 30 miles south of the explosion sites. The condenser-type microphones were located 1500 feet apart in a square array which permits a determination of the azimuth along which the sound wave is moving as it crosses the array. The accuracy of these azimuth determinations is a function of the accuracy with which the time of arrival of the sound wave front at the microphones can be determined. Time of wave arrival was accurate to ± 0.003 seconds, resulting in an overall azimuth error of ± 11 minutes. The locations of the explosion sites and the microphone array are shown in Figure 3. The geographical azimuths from true north are the angles along which the sound wave would travel if the atmosphere were motionless. The observed azimuths are those obtained with the microphone array and these values, being less than the computed values, indicate an integrated wind effect from east to west. Inspection of the meteorological data listed in Tables I and II shows that easterly winds occurred primarily above 55,000 ft MSL.

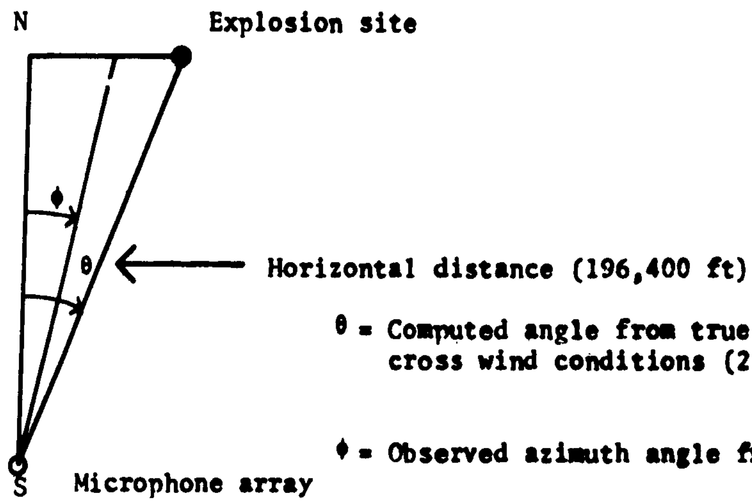
RESULTS

The results of the ray-tracing computations for the rays which travelled a horizontal distance nearly equal to the observed horizontal distance between explosion site and microphone array are listed in Tables III and IV. The listed speed of sound includes the wind component in the plane of travel.

The wind normal to the plane of the propagating sound wave, or cross wind, was determined for 5000-ft layers between the altitude of the explosion and the earth's surface. The integrated cross wind between the surface and explosion altitude was determined by weighting the cross wind within each 5000-ft layer by the sound wave's travel time through that layer.

FIGURE 3

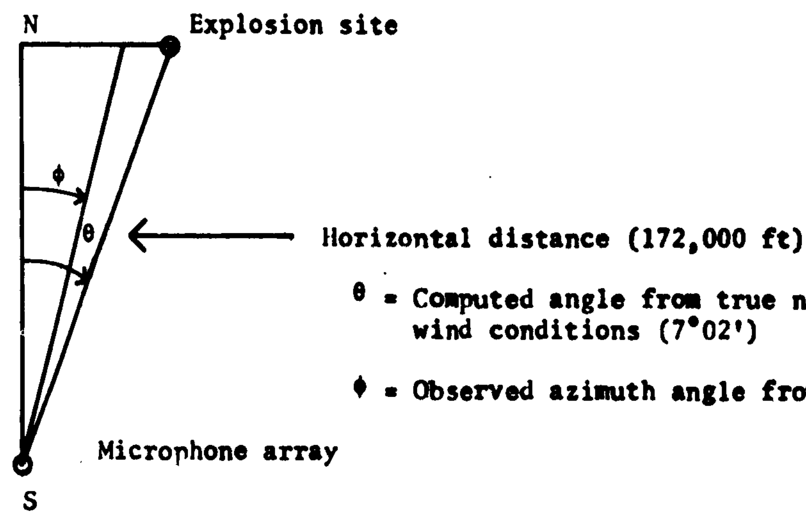
23 July 1962



θ = Computed angle from true north for no cross wind conditions (2°44')

φ = Observed azimuth angle from microphone array (1°36')

27 July 1962



θ = Computed angle from true north for no cross wind conditions (7°02')

φ = Observed azimuth angle from microphone array (5°27')

TABLE I

Meteorological Data - 27 July 1962

Altitude (1000 ft)	Temperature (Degrees Centigrade) 0640-0820	0900-1030	Wind Direction & Speed Degrees/Knots 0640-0820	0900-1030
Sfc	23.3	26.3	150/2	200/3
5	20.8	22.0	170/4	193/4
10	11.3	11.6	227/3	209/4
15	0.3	1.7	53/11	59/6
20	- 7.4	- 7.8	198/2	227/3
25	-16.1	-15.5	187/4	183/11
30	-27.6	-26.1	209/8	202/11
35	-39.2	-39.1	234/11	215/11
40	-52.3	-52.8	227/4	315/2
45	-64.3	-61.1	232/10	252/15
50	-67.9	-68.7	262/16	223/16
55	-72.5	-72.7	175/4	205/4
60	-66.7	-68.3	103/18	124/12
65	-60.3	-63.1	79/25	89/24
70	-58.4	-57.2	86/27	89/27
75	-54.1	-55.2	79/34	94/29
80	-52.3	-52.2	95/36	83/33
85	-45.8	-40.5	90/32	98/29
90	-45.2	-45.2	101/32	99/30
95	-45.6	-45.4	74/41	82/41
100	-43.1	-42.7	83/53	88/51
105	-38.9	-39.1	98/53	100/45

TABLE II

Meteorological Data - 23 July 1962

Altitude (1000 ft)	Temperature (Degrees Centigrade) Observed 0630	Observed 1340	Observed 0900	Estimated Mean From 0630 & 1340	Wind Direction & Speed (Degrees/knots) Observed 0630	Observed 1340	Observed 0900	Estimated Mean From 0630 & 1340
Sfc								
5	25.3	30.0	25.5	27.6	102/2	143/4	327/3	
10	14.0	15.1	14.5	14.5	250/9	265/3	263/9	
15	3.5	3.2	2.9	3.3	265/6	199/11	214/5	
20	- 7.2	- 6.7	- 7.7	- 6.9	185/9	240/12	196/7	215/9
25	-16.5	-15.8	-16.3	-16.1	206/11	220/11	196/15	213/11
30	-27.9	-27.3	-28.9	-27.6	162/12	248/14	220/10	209/10
35	-40.5	-39.4	-40.4	-40.0	183/10	259/19	232/10	234/12
40	-52.3	-51.6	-51.8	-52.0	259/8	313/13	300/9	247/10
45	-62.0	-61.9	-62.2	-62.0	285/9	125/3	325/8	276/3
50	-69.9	-70.3	-68.5	-70.1	48/18	201/14	113/13	97/4
55	-68.6	-70.6	-70.3	-69.6	124/14	72/10		102/11
60	-68.1	-67.1		-68.6	69/9	106/22		96/15
65	-60.7	-61.1		-60.9	78/23	95/11		83/17
70	-57.1	-57.6		-57.3	75/29	107/19		88/23
75	-55.5	-56.2		-55.8	91/32	79/22		85/27
80	-48.7	-50.8		-49.8	105/26	66/28		84/26
85	-48.0	-49.5		-48.7	73/21	82/37		78/29
90	-47.3	-45.0		-46.1	66/21	94/33		83/26
95	-47.2	-42.0		-44.6	70/39	99/34		83/35
100	-43.0	-40.2		-41.6	83/49	103/36		91/42
105	-39.7	-37.0		-38.3		91/32		91/32

TABLE III

Sound Ray Trajectories for 39.3° Ray, 23 July 1962

Altitude (1000 ft)	Speed of Sound (fps)	Horizontal Distance (ft)	Travel Time (sec)
105	1008.7		
100	1001.5	8599	9.9
95	995.0	16939	19.7
90	991.8	25269	29.5
85	986.1	33479	39.2
80	983.6	41588	48.9
75	970.3	49468	54.4
70	967.0	57099	67.8
65	958.9	64573	77.2
60	941.3	71738	86.4
55	937.4	78667	95.5
50	941.5	85600	104.6
45	955.9	92735	113.8
40	979.2	100337	123.2
35	1004.1	108613	132.9
30	1028.7	117730	143.2
25	1054.9	127966	154.1
20	1072.4	139528	165.0
15	1093.6	152747	179.0
10	1117.1	168824	194.2
5	1137.6	190328	213.8
Sfc	1144.2	196117	219.0

TABLE IV

Sound Ray Trajectories for 31.50° Ray, 27 July 1962

Altitude (1000 ft)	Speed of Sound (fps)	Horizontal Distance (ft)	Travel Time (sec)
105	1005.4		
100	999.2	6615	7.7
95	993.3	14961	17.3
90	993.7	23031	26.8
85	986.5	30780	36.1
80	971.7	38407	45.4
75	971.7	45884	54.6
70	967.2	53232	63.7
65	953.9	60403	72.8
60	942.0	67172	81.7
55	932.7	73639	90.4
50	941.1	80009	99.2
45	958.4	86587	108.0
40	977.0	93735	117.1
35	1006.9	101404	126.3
30	1034.5	109646	135.9
25	1056.5	118679	145.9
20	1072.2	128777	156.6
15	1091.2	140551	168.4
10	1110.7	153778	181.3
5	1130.8	168565	195.3
Sfc	1139.1	172115	198.6

The error in the observed azimuth due to the cross-wind effect was then computed from

$$\tan^{-1} \delta = \frac{vt\ (6080.20)}{(3600)\ (d)}$$

where $\delta = (\theta - \phi)$ (Figure 3)

v = total weighted normal wind, knots

t = travel time between source and detector, seconds

d = horizontal projection of geographical distance between source and detector, feet.

The results as listed in Table V show that a correction for the cross-wind effect on propagating sound is required to obtain accurate determinations of the azimuth of the origin of detected sounds.

CONCLUSION

The propagation of sound through the atmosphere is considerably influenced by atmospheric winds both in the speed of the sound wave and the path that it follows. The atmospheric wind normal to the propagation path (cross wind) results in the path's being translated along the wind normal to the path. The effect of a cross wind on sound propagating between source and detector resulted in azimuth errors of 1° 08' and 1° 35' over a 30-mile path. Using meteorological data, a cross-wind correction was determined which reduced the error to 0° 05' and 0° 12'.

TABLE V

Date	Geographical Azimuth	Observed Azimuth	Wind Correction	Observed Azimuth + Wind Correction	Error With Wind Correction (Geographical Azimuth - Observed Azimuth) + Wind Correction	Error Without Wind Correction Geographical Azimuth - Observed Azimuth
23 July 1962	2° 44'	1° 36'	1° 03'	2° 39'	05'	1° 08'
27 July 1962	7° 02'	5° 27'	1° 23'	6° 50'	12'	1° 35'

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FOR THE COMMANDER:

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